# APPLIED CFD IN SUPPORT OF AIRCRAFT-STORE COMPATIBILITY AND WEAPONS INTEGRATION

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## ABSTRACT

The Air Force SEEK EAGLE Office (AFSEO) at Eglin AFB, FL is responsible for performing engineering analyses, developing flight test profiles, and directing real-time flight tests in support of the aircraft and store certification process. The AFSEO engineering areas of expertise include carriage loads, store separations, flutter, ballistics, stability & control, and electromagnetics. Each of these engineering disciplines uses analytical tools to simulate carriage and employment of sophisticated weaponry from advanced fighter aircraft. For most of these disciplines, the ability of the analytical tool to provide a simulation is dependent on aerodynamic data. The accuracy of the simulation, however, is dependent on the quality of the aerodynamic data.

The AFSEO has developed a capability that utilizes Computational Fluid Dynamics (CFD), a technique that numerically solves the equations of fluid motion, to provide high-fidelity aerodynamics in support of the store certification process. CFD has been used within the AFSEO to calculate aircraft/store carriage loads, predict store separation characteristics, and to visualize the flow field phenomena of complex aircraft and weapon configurations. This paper discusses several of the AFSEO CFD activities and shows how the use of high performance computing (HPC) assets contributed to the success of these projects.

First, the mass flow through an air driven electrical generator of an air-to-ground weapon was predicted. The results of this effort demonstrated the importance of CFD's visualization capability in interpreting the interaction between weapon system components and the entire flow field. Next, the separation characteristics of an air-to-ground weapon released from a standard weapon pylon versus modified weapon pylon were compared. These results were used to determine the magnitude of the effort required to certify the modified pylon to the same limits and conditions as the standard pylon. The results also demonstrated CFD's ability to quantify the aerodynamic effects of hardware geometry modifications. Then, the separation characteristics of a laser-guided bomb from the F-15E conformal fuel tank station were predicted. These results demonstrated the diversity and robustness of CFD in providing a complete store separation parametric study. Finally, the separation characteristics of a small bomb from the F-111 weapons bay were predicted. In each case, the AFSEO's dependence on high performance computing (HPC) resources to provide CFD results in a timely manner will be explained and emphasized.

## INTRODUCTION

The AFSEO at Eglin AFB, FL performs engineering analyses and directs real-time flight tests in support of Air Force weapons certification efforts. The primary responsibility of the AFSEO is to provide the warfighter with the maximum combat capability for all weapon systems or combination of weapon systems. Using engineering analyses, flight test results, or a combination of both, the AFSEO determines acceptable flight limits and conditions in which the warfighter may safely carry and employ a weapon system. To accomplish this task, the AFSEO maintains a core of engineering expertise in the disciplines of aircraft and store loads, store separations, aircraft flutter, aircraft stability and control, vibrations, ballistic accuracy, safe escape, electromagnetics, and computational fluid dynamics.

With the exception of electromagnetics, aerodynamics and/or the interaction of the aerodynamics with the aircraft influence each of these disciplines. To understand this influence on aircraft/store compatibility issues, the AFSEO uses a variety of modeling and simulation (M&S) tools that are designed to predict critical flight regimes and simulate test conditions for advanced fighter aircraft carrying and employing complex weapon systems. These M&S tools use computer generated models and software to evaluate the combined effects and functionality of both the aircraft and weapons in real world scenarios. Because of the increased costs of flight-testing and the hardware used to support it, more emphasis has been placed on the use of M&S to reduce the certification costs and to increase margins of safety for all weapons programs.

Many of the M&S tools used within the AFSEO require aerodynamic data for execution. The accuracy of M&S predictions is dependent on the accuracy of the aerodynamic data available. Historically, the AFSEO has used wind tunnels and empirical methods to provide these aerodynamic data. Both of these techniques are excellent sources of aerodynamic data and are capable of providing large quantities of data. Current wind tunnel test techniques, however, are becoming too costly or are not capable of providing accurate flowfield predictions for the next generation aircraft and weaponry. In addition, hardware fabrication costs are increasing and model scale effects alter the physics of the problem being solved. Likewise, most empirical methods use linear theory assumptions in their formulation and depend on a pre-existing source of aerodynamic data. Over the past ten years, however, the AFSEO has been developing a M&S tool to supplement the wind tunnel and empirical methods and reduce flight test requirements. CFD is a numerical approach used to solve the fluid equations of motion while maintaining conservation of mass, momentum, and energy. It is a computer simulation tool that eliminates the physical limitations associated with the wind tunnel and the linear assumptions associated with empirical methods. At present, CFD capabilities are being used to estimate carriage loads and predict time accurate store separations within the AFSEO. CFD is also being used to analyze weapon components and provide flow field visualization in support of weapons development programs.

Regardless of its use, the T&E community continues to criticize CFD because of the time required to perform the CFD process (i.e., grid generation, grid assembly, flow solution generation, and data reduction). Often times, the use of CFD does require many hours of computer processing time and large amounts of memory due to the geometric complexity of the problem, the grid density required to resolve the physics of the problem, or both. Great accomplishments have been made which address the time issue associated with CFD. Because of the work and success in the areas of grid generation and parallel computing, CFD continues to evolve as an M&S tool. CFD is becoming more valuable because of its ability to eliminate current ground test limitations and the diversity of the problems it is capable of addressing. The means by which CFD is used and the way it will look to the T&E community in the future is highly dependent on high performance computing (HPC) resources. These resources must continue to be available and easily accessible to the CFD community. They must also provide users with the latest computer architecture technology, large memory banks, large storage areas, and numerous processors. These items are critical to CFD and its ability to continue supporting the Air Force warfighter.

The contents of this paper will show the results of several projects that have benefited from CFD capabilities through the use of HPC resources. The following examples are included: predictions of the mass flow through and flow field characterization in the vicinity of an electrical generator; the effects of a hardware geometry modification on the separation characteristics of an air-to-ground weapon; a store separation parametric study for a laser guided bomb from the conformal fuel tank station of the F-15E; and a prediction of the separation characteristics of a weapon from the F-111 weapon bay.

## BEGGAR DESCRIPTION

The Beggar code was used to supply the CFD solutions for the applications presented. Beggar was originally developed by the Wright Laboratory Armament Directorate at Eglin AFB, Florida in the early 1990's and has been extensively modified by the AFSEO CFD team. Beggar uses an upwind numerical technique combined with a Newton relaxation scheme to solve the Euler or Navier-Stokes equations of fluid motion. It employs a domain decomposition method to ease the grid generation tasks and to reduce computational requirements. Beggar gives the user the flexibility of using blocked grids, patched grids, or overlapped (Chimera) grids to decompose complex geometries into smaller subdomains. Beggar has a unique automated grid assembly procedure to create a communication network for overlapped grids. This procedure combines octree and binary space partitioning tree data structures to form a composite grid system of overlapped grids. The flow solver uses the Steger-Warming scheme or the Roe scheme with limiters to solve the flux vector equations. Beggar currently contains multiple 1-equation turbulence models including the Baldwin-Barth, the Baldwin-Lomax, and the Spalart-Allmaras models. The Beggar flow solver also includes a fully coupled six-degree of freedom model to provide a time-accurate store separation prediction capability.

## EGLIN CFD APPLICATIONS

The Eglin CFD team was highly dependent on HPC resources over the past year to support several projects for both developmental weapons programs and the AFSEO. The following paragraphs contain a brief description of each project, discuss how CFD was used to address the problem, give a summary of the results obtained, and provide program specifics as they relate to HPC. All of the applications discussed in this report used Origin 2000 HPC resources.

**Electrical Generator Analysis –** The purpose of this effort was to predict mass flow through an air driven electrical generator. The generator, figure 1, is used on various weapon systems to supply power to the guidance and control (G&C) unit. It is designed with an internal turbine that drives a generator as air flows past the blades thereby producing an electrical current. To function properly, the generator requires a minimum amount of mass flow to initially overcome the design torque of the turbine and later provide enough rpm to generate sufficient levels of voltage for the application. If these design thresholds are not achieved or maintained during flight, the generator will stop and the G&C unit will malfunction. During recent flight testing, malfunctions did occur which prompted a detailed flow field study of the generator on multiple weapon systems. Three areas were identified as possible causes for the malfunction: 1) the location of the generator relative to the carriage lug; 2) vortices generated by the body strakes impinging on the generator; and 3) inadequate mass flow through the generator.

**Figure 1. Electrical Generator**

The electrical generator is positioned in the fuze well for every weapon system that it is used with. The fuze well is located approximately 7.5 inches aft of the carriage lug for most weapons. Figure 2a depicts the lug and the generator positioned on a 2000-pound class weapon. Because of its proximity to the lug, there was a concern that the flowfield disturbance created by the lug was propagating downstream and interfering with the flow into the generator inlet. CFD solutions were generated for various flight conditions to investigate this phenomenon and determine if these disturbances were causing the malfunctions. Figure 2b shows the computed flowfield disturbance in the form of Mach number contours propagating downstream to the generator position. The results show that the lug does have an effect on the flow field entering the generator. The degree of this effect and its level of detriment are still being investigated.

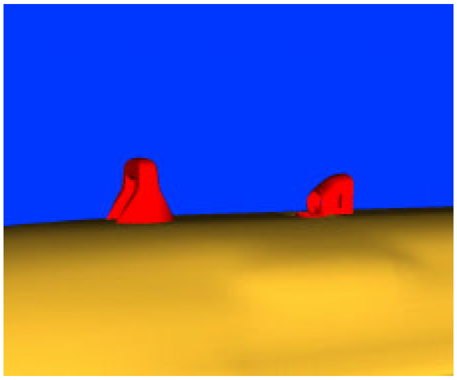


Figure 2a. Carriage Lug and Generator Geometry.

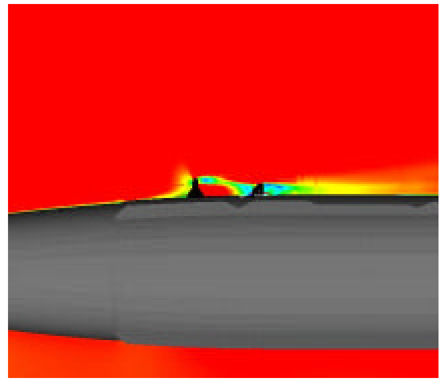


Figure 2b. Lug Disturbance Propagation

The weapon systems of interest for this effort are also equipped with strakes that extend from just ahead of the forward carriage lug to just behind the aft carriage lug (see figure 3), or approximately 40% of the length of the body. The CFD solutions were used to visualize the behavior of the vortices being generated by the strake leading edges. Figure 3 also shows red particle traces which represent these vortices. The results indicate that the vortices have no direct influence on the generator.

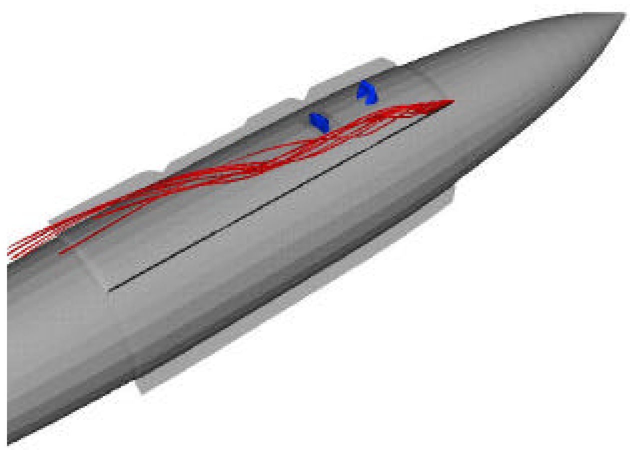


**Figure 3. Particle Traces of Strake-Induced Vortex**

Finally, the CFD solutions were used to calculate the mass flow of air through the generator inlet. The solutions indicate that the mass flow through the generator does drop below the minimum functional requirement at certain flight conditions. At the time of this writing, the exact cause of this drop was still under investigation.

**F-16 Air-to-Ground Weapon Separation –** The purpose of this effort was to predict and compare the separation characteristics of an air-to-ground weapon when released from a standard weapon pylon and a modified weapon pylon. The standard weapon pylon was modified to include the capability to carry and dispense chaff and flares. The modifications needed to provide this capability included increasing the overall length of the standard pylon and increasing its width over the last third of the geometry. Figures 4a and 4b show the standard pylon and the modified pylon, respectively.

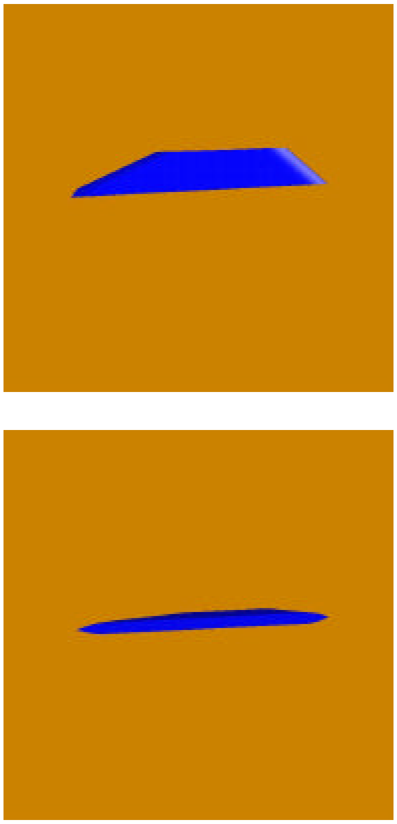


**Figure 4a. Standard Weapon Pylon**

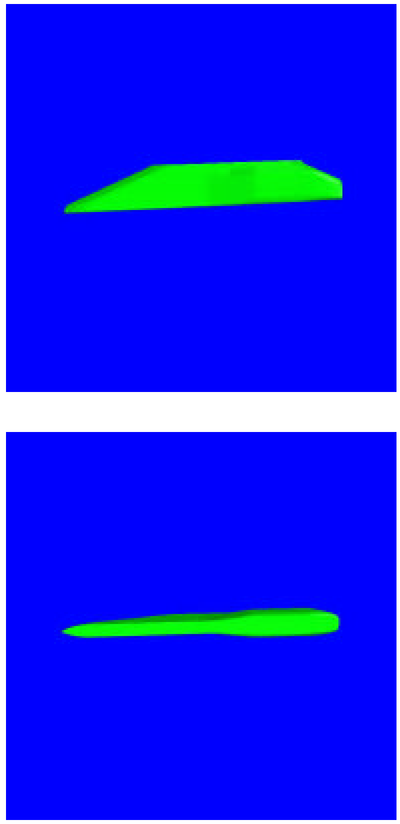
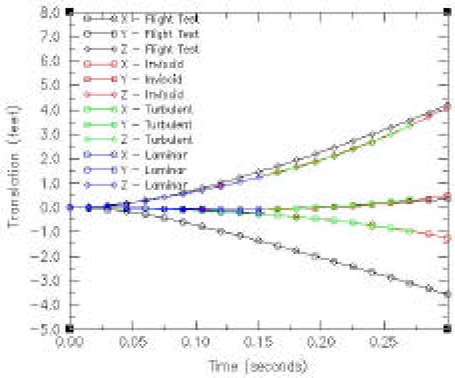


**Figure 4b. Modified Weapon Pylon**

Separation trajectories were generated using CFD for both pylons at one test condition. Two cases were run for each pylon at the test condition. The ejector forces were varied for each case. Figures 5a and 5b give plots of the translations and angular orientations of the weapon throughout the trajectory. The results show that the modified pylon effects only the pitch and roll angular orientation. The data trends for all other separation parameters for both cases compare very well. The changes in angular orientations by the modified pylon can be explained by the fact that this pylon reduces the magnitude of a high-pressure region located just forward of the weapon tail section. This reduction gives the tail section more influence on the separation and produces a stronger nose-down pitching moment.



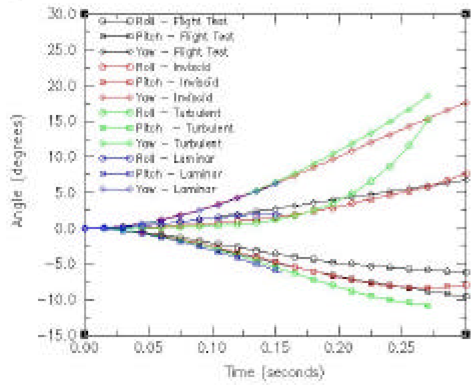




**Figure 5a. Air-to-Ground Translations Weapon Translations**

**Figure 5b. Air-to-Ground Angular Orientations**

**F-15E Laser Guided Bomb Separation –** The purpose of this effort was to calculate the carriage aerodynamic loads on the canards of a laser guided bomb and to predict its separation characteristics from the forward inboard conformal fuel tank station of the F-15E. The bomb used in this effort is equipped with forebody canards that are designed to be free-floating (i.e., aligned with the oncoming direction of flow) during carriage. The study was prompted by recent flight tests in which pilots reported the canards were in the fully deflected position at the time of release. The canards can be deflected to a maximum angle of attack of $15^o$ and, when in that position, rest against a physical stop. Deflected canards indicate that the flowfield environment around the weapon has significantly different characteristics than the freestream flowfield. Figure 6 shows the test configuration for this effort, which includes a targeting pod shown in blue, mounted to the underside of the F-15E. As can be seen, a clean weapon separation from this station is critical since contact with the pod could result if the weapon is subjected to a non-uniform flowfield environment.

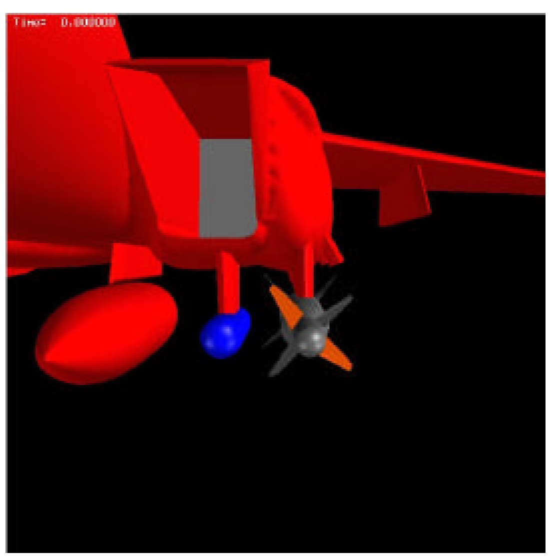


**Figure 6. F-15E Laser Guided Bomb Separation Configuration**

The first phase of this effort was to calculate the carriage loads exerted on the canards in the fully deflected position. This approach was used to determine the resulting direction of the aerodynamic load on the canards. A resulting force in the direction of the physical stop would verify that the canards were indeed fully deflected during carriage. A resulting force in the direction opposite the stop would suggest only that the canards were not in the fully deflected position during carriage. The results for this phase produced a resultant force acting in the direction opposite the physical stop, indicating the canards were not fully deflected as reported by the aircrew.

The second phase of this effort used CFD to generate separation trajectories for two geometric cases: a case with the forebody canards removed; and a case with fully deflected canards. The first test case was designed to model the canards as free-floating bodies. This assumption was used because free-floating canards generate no aerodynamic forces on the bomb and are, therefore, equivalent to removing them from the calculations. The trajectory for this case was run to 0.35 seconds, or approximately 6 feet below the carriage position. Figure 7 shows a front view of the aircraft with “ghosted” images of the bomb as it separates.

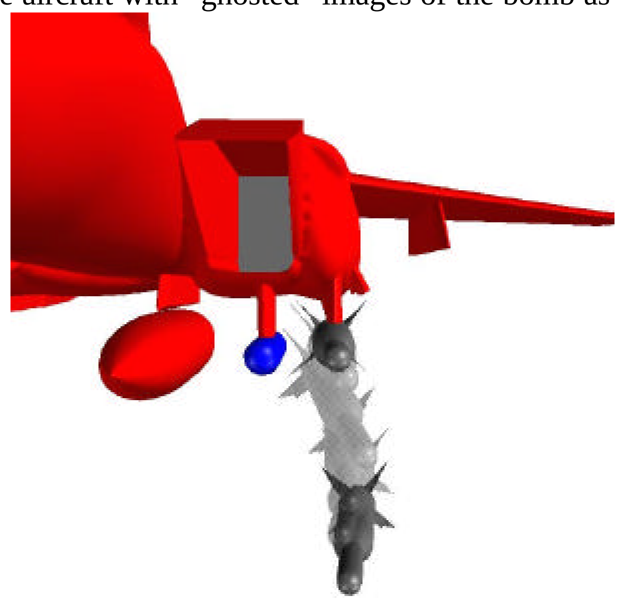


**Figure 7. Front View of Case 1 Separation**

The results showed that the bomb yaws slightly outboard and nose down during the separation event and that it does not contact the targeting pod. The results were also used to measure the closest distance between the bomb and the targeting pod. The closest distance for this case was predicted to be 10 inches between the aft section of the bomb body and the pod.

The second test case predicted the trajectory with the canards in the fully deflected position for the first 0.20 seconds and then with the canards removed for the remainder of the simulation. Although the results of phase one indicated that the canards were not fully deflected, the angle at which the canards were deflected during carriage was unknown. Therefore, the simulation was run with the canards modeled in the fully deflected position to provide a worst case prediction. The trajectory for this case was run to 0.35 seconds, or approximately 6 feet below the carriage position. Figure 8 shows a front view of the aircraft with "ghosted" images of the bomb as it separates.

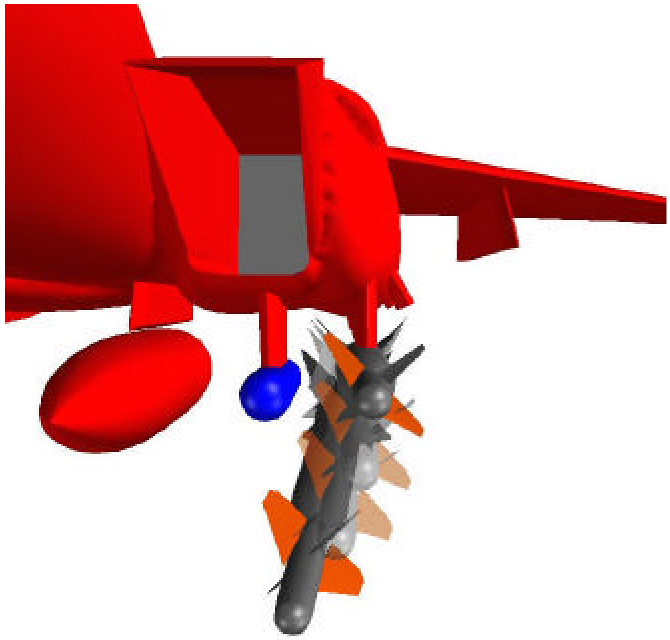


**Figure 8. Front View of Case 2 Separation**

The results for this case showed that the bomb pitches slightly nose down during the separation event and that the weapon translates slightly more inboard than the previous case. However, the weapon still does not contact the targeting pod. The closest distance was again measured and was predicted to be 6 inches between the inboard canard and the pod.

**F-111 Small Smart Bomb Separation** – The purpose of this effort is to predict the separation characteristics of a small smart bomb from the F-111 weapons bay. The small smart bomb has a supersonic operational envelope, which creates a weapon carriage and employment concern. Figure 9 shows a cutaway of the F-111 weapons bay with two small smart bombs installed. The plan is to separate both of the weapons at $3.5^{o}$ angle of attack, $54^{o}$ wing sweep, and various subsonic and supersonic Mach numbers.

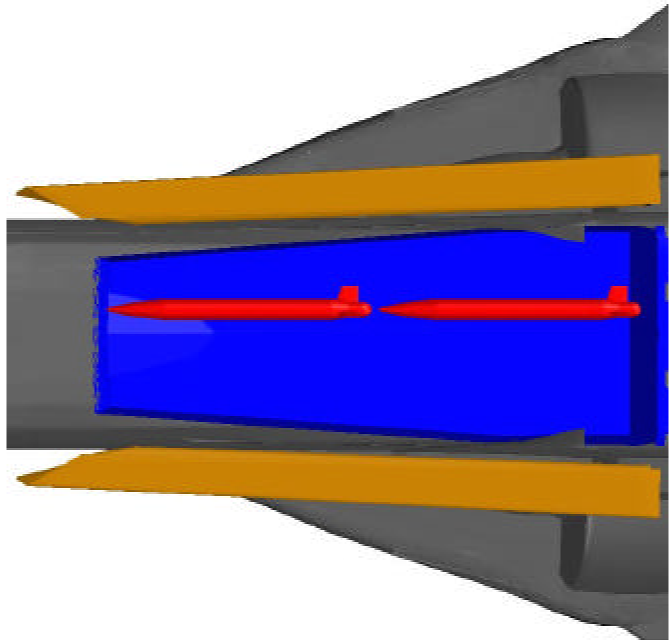


**Figure 9. F-111 Small Smart Bomb Configuration**

This effort has been divided into three phases. The first phase was a proof of capability phase. During this phase, CFD was used to compute the trajectory on a generic missile released from a generic "shoe box" cavity. The selected configuration was wind tunnel tested several years ago at the Arnold Engineering Development Center and represented the most comprehensive data set available for validation.

The second phase is the verification phase. This phase will predict the separation trajectory of an air-to-ground bomb from the F-111 weapons bay. Due to the age of the flight test data being used for this phase, the only information available for comparison with the CFD results is flight test film coverage. Therefore, this phase will provide a qualitative assessment of the CFD predictions only.

The third phase of this effort is to predict the separation trajectory of the small smart bomb. To date, the small smart bomb has been gravity released from its carriage position with no simulated airflow. This technique is used to ensure that there is adequate grid overlap throughout the path of the trajectory so that proper communication links (used in conjunction with chimera CFD methods) may be established. The final results of phases II and III of this project were unavailable at the time of this writing since the project is currently in progress.

## COMPUTER RESOURCES

The computer resource requirements played a vital role in the success of these four projects. For each project, the use of multiple processors and large quantities of memory were required to meet the project goals and deadlines. The following table shows the type of computer used for the CFD effort, the average number of processors used to produce the CFD solution, and the maximum amount of memory required for the solution.

| Project | Avg. Processors | Max. Memory |
|---|---|---|
| Electrical Generator Analysis | 16 | 3 Gb |
| F-16 Air-to-Ground Weapon Separation | 20 | 6 Gb |
| F-15E Laser Guided Bomb Separation | 30 | 8 Gb |
| F-111 Small Smart Bomb Separation | 40 (est.) | 20 Gb (est.) |

## CONCLUSION

CFD has become a major M&S tool for Team Eglin to address weapon system issues for the Air Armament Center at Eglin AFB, Florida. The diversity of CFD as an M&S tool has been demonstrated via the projects presented in this paper. Although they may seem complex, these type problems are typical of the challenges that Team Eglin faces and common to the CFD community. As weaponry and aircraft become more sophisticated, the typical problem will be an order of magnitude more complex. The test and evaluation (T&E) of developmental systems will be much more dependent on M&S tools to provide timely and accurate analytical predictions at a lower cost. Multi-processor computer systems with fast CPU's and large amounts of memory are the key element in this scenario. Likewise, the continued use and growth of CFD as an M&S tool is critically dependent on the availability of computational resources that can solve problems like those presented herein in a reasonable amount of time.

This paper demonstrates the importance of HPC resources to the Eglin AFB CFD capability. These resources are used on a daily basis to provide support to the modern day warfighter. These resources must continue to be available to teams like the Eglin CFD team and must be maintained to the highest level of available technology. Through the use of HPC resources, CFD and the CFD team will be able to provide maximum combat capability for the warfighter throughout the 21st century and beyond.